Quarterly Progress Report

N01-NS-1-2333

Restoration of Hand and Arm Function by Functional Neuromuscular Stimulation

Period covered: January 1, 2006 to March 31, 2006

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Contract abstract

The overall goal of this contract is to provide virtually all individuals with a cervical level spinal cord injury, regardless of injury level and extent, with the opportunity to gain additional useful function through the use of FNS and complementary surgical techniques. Specifically, we will expand our applications to include individuals with high tetraplegia (C1-C4), low tetraplegia (C7), and incomplete injuries. We will also extend and enhance the performance provided to the existing C5-C6 group by using improved electrode technology for some muscles and by combining several upper extremity functions into a single neuroprosthesis. The new technologies that we will develop and implement in this proposal are: the use of nerve cuffs for complete activation in high tetraplegia, the use of current steering in nerve cuffs, imaging-based assessment of maximum muscle forces, denervation, and volume activated by electrodes, multiple degree-of-freedom control, the use of dual implants, new neurotization surgeries for the reversal of denervation, new muscle transfer surgeries for high tetraplegia, and an improved forward dynamic model of the shoulder and elbow. During this contract period, all proposed neuroprostheses will come to fruition as clinically deployed and fully evaluated demonstrations.

Summary of activities during this reporting period

The following activities are described in this report:

- *Target feedback training for multiple myoelectric signal control*
- *Development of an EMG controlled computer mouse emulator*
- *Proximal stimulation patterns for a high tetraplegia neuroprosthesis*
- *Evaluation of nerve cuff electrodes in high tetraplegia*
- *Laboratory system for FES controller development*
- *Subject recruitment for neuroprosthesis implementation*

Overview

The activities in this quarter focused on the implementation of the high tetraplegia neuroprosthesis. As discussed in last quarter's progress report, an individual with C1-level tetraplegia has been implanted with 24 stimulation electrodes (15 muscle electrodes and 9 nerve cuff electrodes) and four myoelectric signal (MES) recording electrodes. The subject had been performing a daily electrical stimulation exercise routine to strengthen her muscles, and was practicing controlling her myoelectric signals via a simple LED-based biofeedback program.

This quarter's effort has focused on more sophisticated MES training techniques and on the development of the initial functional stimulation patterns. These items are described below. One issue that has arisen is the spasticity and increased tone of some of the subject's muscles, which often opposes the functional movements we are trying to attain. We are working with the subject's clinical team to reduce the spasticity and increased muscle tone through a combination of occupational therapy and anti-spasticity medication.

Target Feedback Training for Multiple Myoelectric Signal Control

Contract section: E.1.a.vi.4.3. Implementation of neuroprostheses in high tetraplegia

Abstract

The high-tetraplegia subject has four implanted MES recording electrodes to control her implanted FES system. By activating the correct muscles, she generates four signals which are sent to the external hardware for processing. This section describes how we are training the subject to use her MES, and describes some signal processing approaches used to isolate the four signals.

Methods

The FES user has many individual degrees of freedom to control. Because we have a smaller set of control signals—the MES—than degrees of freedom, we only operate two degrees of freedom at a time, with a switch to change between sets. In this way, our subject can, for instance, control the position of her hand in space, then switch modes and operate her hand to grasp an object.

The MES signals are recorded from muscles on the neck and shoulder, and so are unrelated to the command task. To train the user and give her practice with the signals, we use a software task involving several targets and a cursor. The subject is able to control the cursor with her MES, and the goal of the task is to move the cursor to the targets. Targets appear one at a time, and the subject has ten seconds to move the cursor in to the circular target. The cursor must remain in the target for one second to count as a "hit."

The software records the MES signal, and adaptively adjusts the weights given to each of the four recordings. Because we know the desired command (the target location), we can train the software to recognize what MES signals the user generates in response to that desire. In this way, the program learns over time the best way to respond to a given MES input.

Results

The software has been setup on a computer in the user's home, so that she can train daily on controlling her MES signals. Figure 1 shows a screenshot of the software in action.

Next Quarter

The user will continue to train with her MES signals at home during the next quarter. The variations in the MES signals and the user's ability to track targets will be monitored.

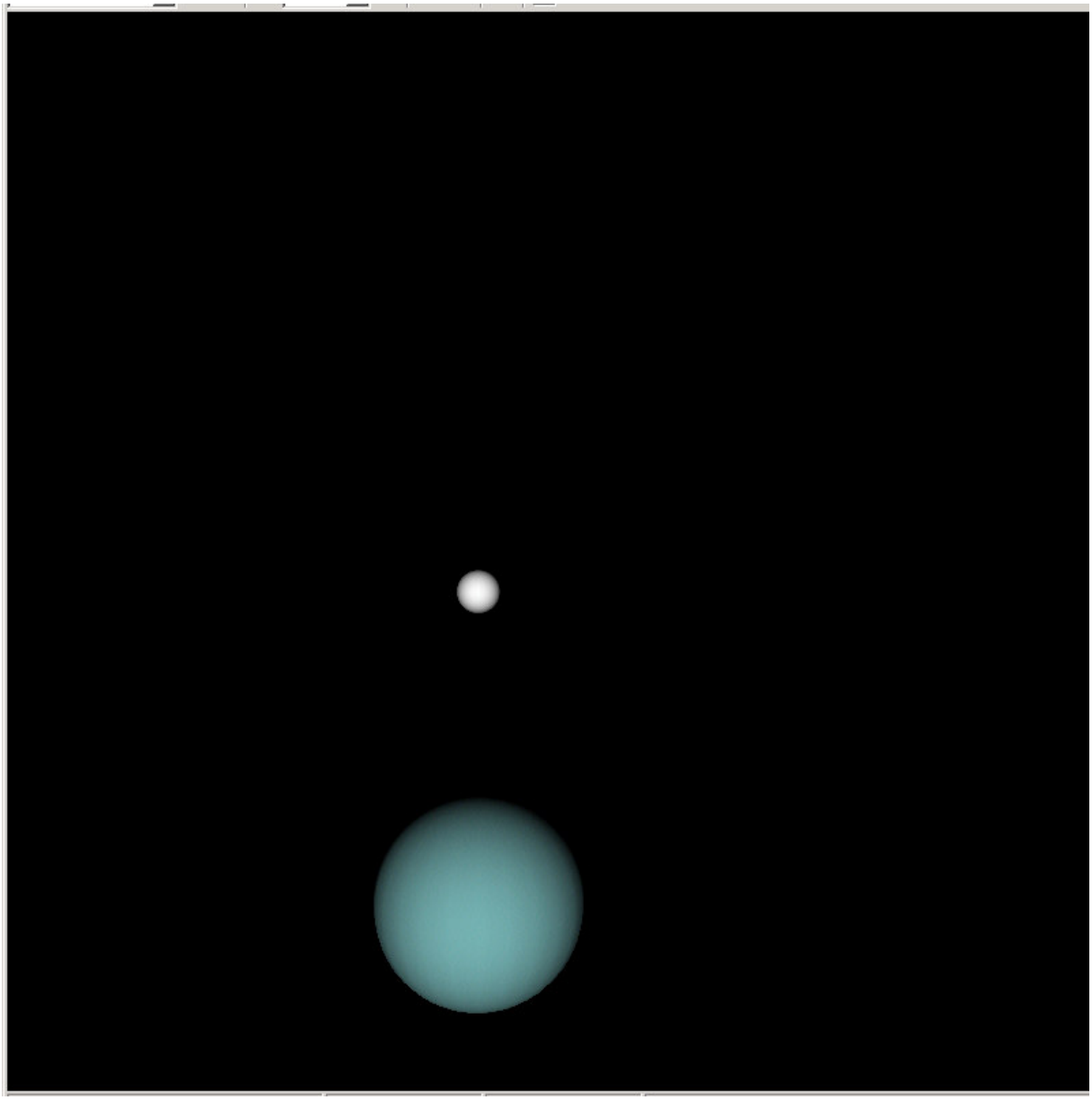

Figure 1. The MES training software. The small white ball is the cursor, under MES control. The larger blue ball is the target, which the subject is trying to reach with the cursor. Once the cursor is in the target for one second, the attempt is recorded as a success, and a new target appears. The subject has 10 seconds to reach each target.

Development of an MES-Controlled Computer Mouse Emulator

Contract Section: E.1.a.iv. Command Sources for High Tetraplegia

Abstract

A mouse emulator was developed to allow a subject to control a computer cursor using her implanted MES electrodes as a command source. The emulator consists of a single board

computer running a custom control system that sends motion signals to a modified PC mouse. Input to the system comes from the user's implant controller and the outputs are PS/2 compatible two-dimensional mouse signals. The user was able to move the cursor about the screen to operate various common applications. Utilities were also written to adjust and reset the mouse if necessary.

Methods

The mouse emulator consists of both hardware and software components that convert the user's voluntary MES signals into two-dimensional mouse commands. The relationship of the components and the flow of information through the system can be seen in Figure 2.

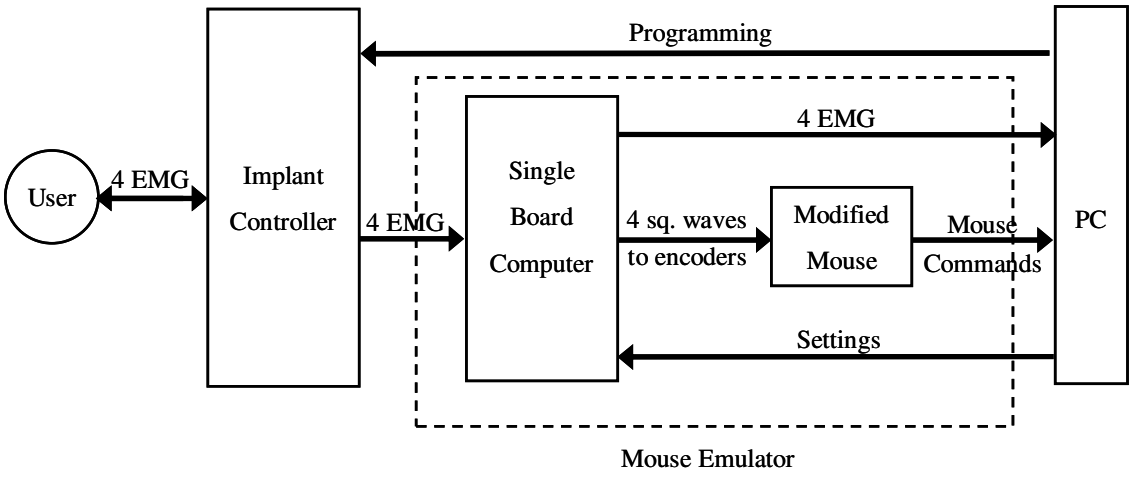

Figure 2. Schematic of EMG controlled mouse emulator (dotted line) with inputs and output components. Arrows indicate information type and flow.

Hardware:

A single board computer (SBC) was used as a controller for converting MES signals into mouse command signals. The SBC software is detailed below. The SBC takes in a 4 byte serial data stream (RS-232, 8N1, 115.2kbps) containing the amplified and rectified MES amplitude recorded by the implanted stimulators at 12.5 Hz. The outputs are four variable frequency digital square wave signals sent to the modified mouse.

A standard Microsoft three button PS/2 mouse was modified such that it was able to receive electrical input signals that mimicked the same signal produced by mouse motion during normal operation (Figure 3). Using the 4 square waves passed by the SBC, the mouse interpreted the input as variable speed motion in two dimensions as if the mouse itself were moving. These "faux motion" signals entered the mouse at the output pins of the motion encoders. Connections were also made to the mouse buttons such that any button with a 1/8" jack connector, or a logical-high signal from the SBC, can be used by the subject to activate button presses. This system can be used with any PC since the output is a standard PS/2 mouse signal.

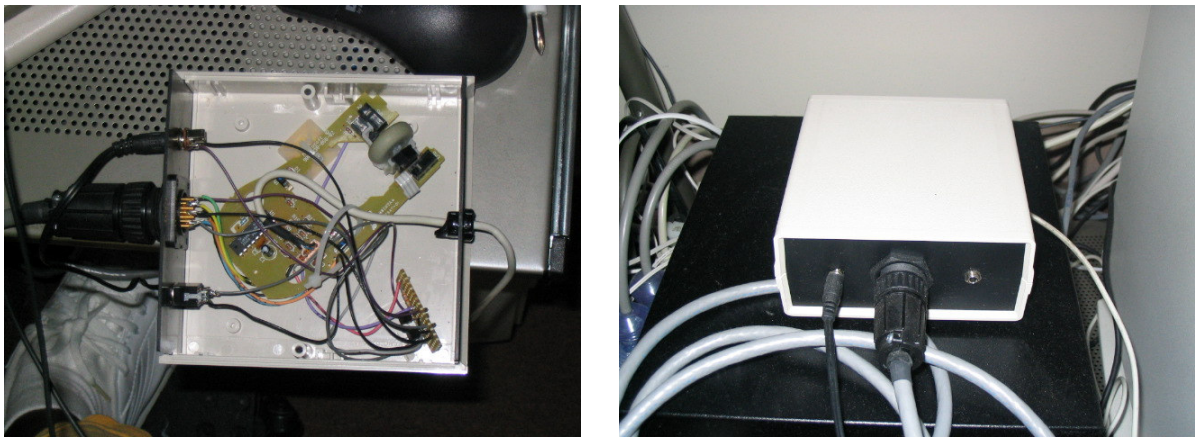

Figure 3. Photograph of modified mouse (left) and external view (right) illustrating button jacks and cable to SBC.

Software:

The control system for the SBC was programmed using xPC Target from Mathworks. The controller consists of a data pass through to send received MES signals to the PC, two motion algorithms, and a speed to frequency converter (Figure 4). There are also two software switches for switching between algorithms and turning emulator operation on or off.

The first algorithm used a weighted sum of the four input MES signals to provide proportional speed control of the cursor. The weights were derived through a target acquisition training regimen on the PC and were updated after each training session. This mode of operation approximates the normal motion of the computer cursor, with higher levels of muscle activity producing faster motion.

The second algorithm explored used a gated ramp where muscles activity above a pre-set threshold produced constant speed motion in one direction. Logic is included to minimize dual activation in the case of cross-talk between electrodes. This mode of operation is currently used in other FES systems for hand grasp.

Two desktop utilities were also developed for use with the mouse emulator. The first is a graphical calibration tool which allows the user to adjust the threshold used with the gated ramp algorithm. This tool also saves the adjusted thresholds to the PC hard drive in the event that the emulator is reset. The second utility is a setting restore tool that resets the mouse to its last saved configuration in the event that the system is powered off or manually reset.

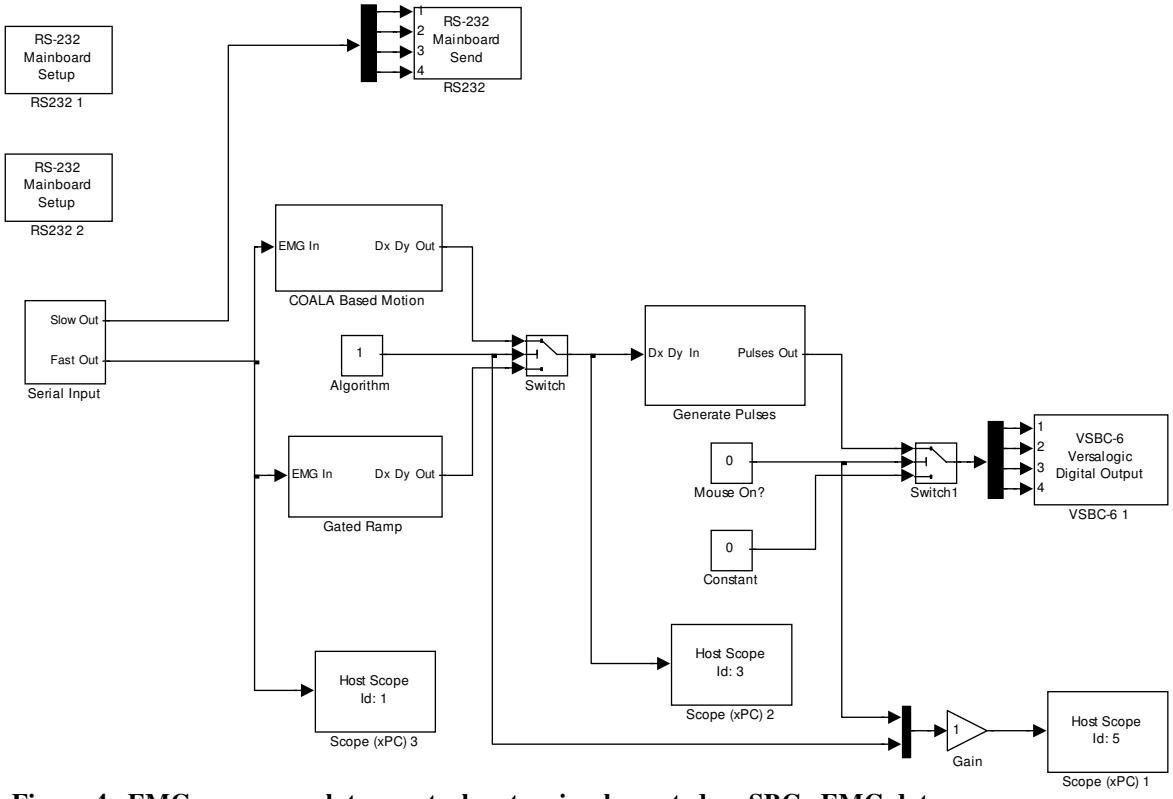

Figure 4. EMG mouse emulator control system implemented on SBC. EMG data comes in via the serial input on the far left and progresses to the digital output on the right. The software switches are controlled by parameters set by software on the

Operation:

User signals were collected by four implanted MES recording electrodes on both sides of the platysma, left trapezius, and the right auricularis (Figure 5). These signals were passed from the implants to the external controller, which in turn sent the MES values to the SBC. From there, the MES values were processed using one of the two motion algorithms. The speed calculated by these algorithms was then converted into the corresponding input frequency to the mouse encoders to produce cursor motion at the determined speed.

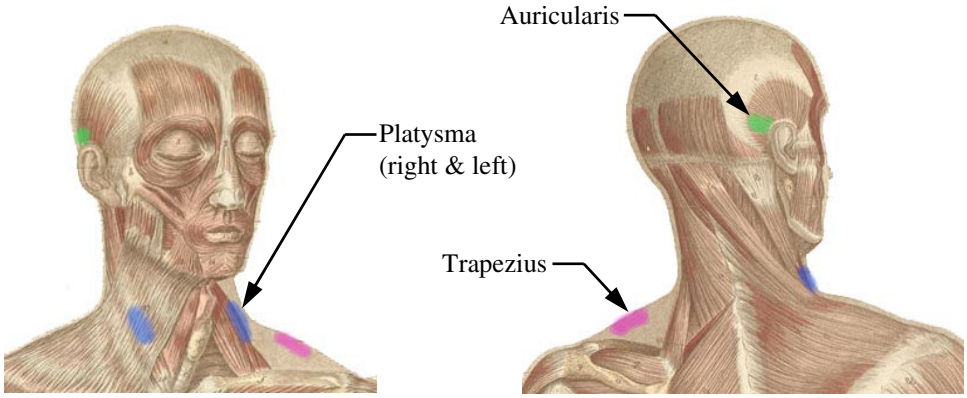

Figure 5. Muscles used to control mouse emulator.

Results

The proportional speed control was too unstable to be used as a control signal for long term operation. During training, the system was able to produce useful motion, but outside of the training program, the cursor motion quickly became erratic and had significant drift in one direction with no user input.

The gated ramp algorithm displayed better results, despite being less natural motion (Figure 6). Thresholds were stable over time, requiring about 10% adjustment week to week. Without adjustment, the mouse emulator would begin to have a slow drift in one direction. The commands for the left and up directions show a high degree of cross-talk. This is most likely due to their close physical proximity (left platysma and trapezius respectively) as well as co-activation during strong voluntary contraction. The right and down directions were not as coupled as they use very disparate muscles (right platysma and auricularis respectively).

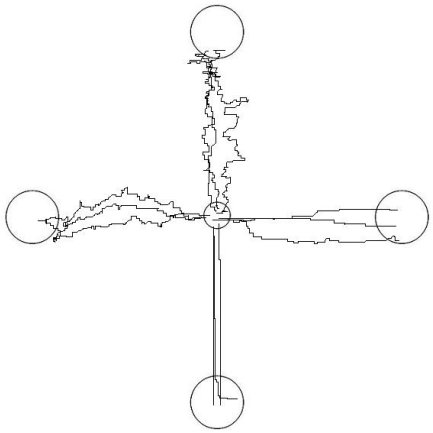

Figure 6. Screen capture of directed one-dimensional cursor motion.

Using the system, the subject was able to operate various PC functions, including playing games and navigating the desktop. The system provided valuable entertainment and training opportunities to the subject.

Next Quarter

A software version of the mouse emulator is currently in development and will be implemented next quarter. This would eliminate the SBC and modified mouse, reducing the overall complexity of the system. The best performing of either the hardware or software versions will be used to evaluate the effectiveness of cervical EMG signals to control two-dimensional motion with both an impaired subject and healthy subjects using surface EMG signals.

Proximal Stimulation Patterns for a High Tetraplegia Neuroprosthesis

Contract section: E.1.a.ii. Model-based development of neuroprosthesis for high tetraplegia

Abstract

Using the musculoskeletal model of the arm developed previously, muscle activation patterns were calculated to restore simple reaching movements. These patterns were tuned and tested with the high tetraplegia subject. The goal was to make an initial evaluation of the model predictions in the presence of possible stiffness and spasticity.

Methods

The movement we focused on was reaching towards a knee-level surface, and then towards the mouth (simulating eating). The kinematics for this movement were recorded from

able-bodied subjects using the Optotrak motion analysis system. The data were then used as inputs to the arm model, which calculated activation patterns corresponding to this movement.

Results

Figure 7 shows the pattern we used for the "eating" movement. In the middle of the pattern there is a "resting" period, during which there is no muscle stimulation and the arm is resting on the lap. To the left is the stimulation needed to bring the arm towards the mouth, and to the right the stimulation needed to extend the arm towards the table. With these stimulation levels, the high tetraplegia subject did not achieve able-bodied kinematics, due to arm stiffness and spasticity.

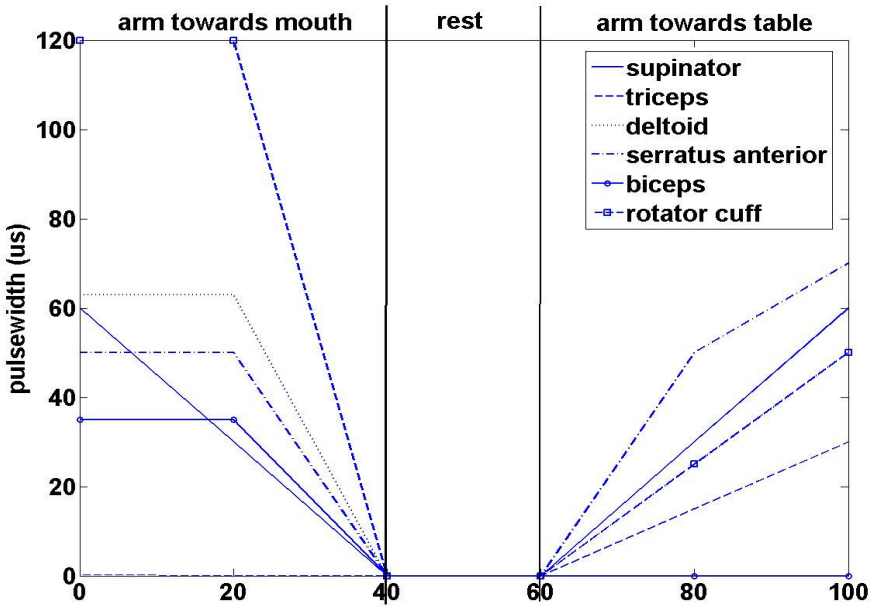

Figure 7. Stimulation patterns for the six muscles used in the "eating" movement.

Next quarter

The movements resulting from muscle stimulation patterns will be recorded using the Optotrak system. These recordings will demonstrate the effect of occupational therapy and anti-spasticity medication on the arm stiffness and range of motion. When this has sufficiently improved, new stimulation patterns will be implemented for restoration of a wider range of movements. A mobile arm support will also be used to counteract some of the effects of the arm stiffness and will allow us to evaluate additional functional stimulation patterns.

Evaluation of Nerve Cuff Electrodes in High Tetraplegia

Contract section: E.1.a.vi.4.3. Implementation of neuroprostheses in high tetraplegia

Abstract

This report covers the testing of nerve cuff electrodes implanted in a subject with C1-C2 incomplete spinal cord injury. Spiral nerve cuff electrodes were implanted on six upper extremity nerves. Single-contact electrodes were placed on the axillary and suprascapular nerves to stimulate the deltoid, infraspinatus and supraspinatus. Four-contact electrodes were placed on the radial and musculocutaneous nerves to stimulated the biceps, brachialis, triceps, wrist extensors, finger extensors, supinator and some thumb muscles. The previous quarterly report presented results from the 16 weeks of percutaneous testing including long term stability, selectivity and current steering. Single-contact electrodes were also placed on the thoracodorsal and long thoracic nerve to stimulate the latissimus dorsi and serratus anterior muscles. These cuff electrodes were not evaluated percutaneously. This report presents follow up data recorded from week 35.

Methods

Weekly experiments were performed from 5 to 16 weeks post implant (Table 1).

Week	5	6	7	8	9	10	11	12	13	14	15	16	35
Surface EMG recruitment	X							X			X	X	X
Percutaneous EMG recruitment				X			X				X		
Tetanic moment measurements		X	X		X			X	X	X	X		

Table 1. Schedule of testing for subject #1.

Electromyography Recordings:

For this quarter, surface EMG recordings were used to evaluate recruitment of each nerve. Surface twitch recruitment curves were generated using single channel, square, biphasic stimulation at different values of pulse width and pulse amplitude modulation. These trials were run using the universal external control unit (UECU) and the implanted IST stimulator. The curves from 35 weeks were compared to the percutaneous phase.

Results

Electrode Positional Stability:

To determine if the electrodes move during and after the surgery, the recruitment curves generated intraoperatively were compared with curves generated 5 and 16 and 35 weeks post implant (Figure 8). At all times, stimulation of channel 1 of the radial nerve resulted in triceps activation before the other muscles, while stimulation of channel 3 resulted in activation of triceps last. Qualitatively, the selectivity appears to have improved following electrode encapsulation. This shows that the nerve cuff electrodes did not move significantly during the implant of additional hand and arm electrodes.

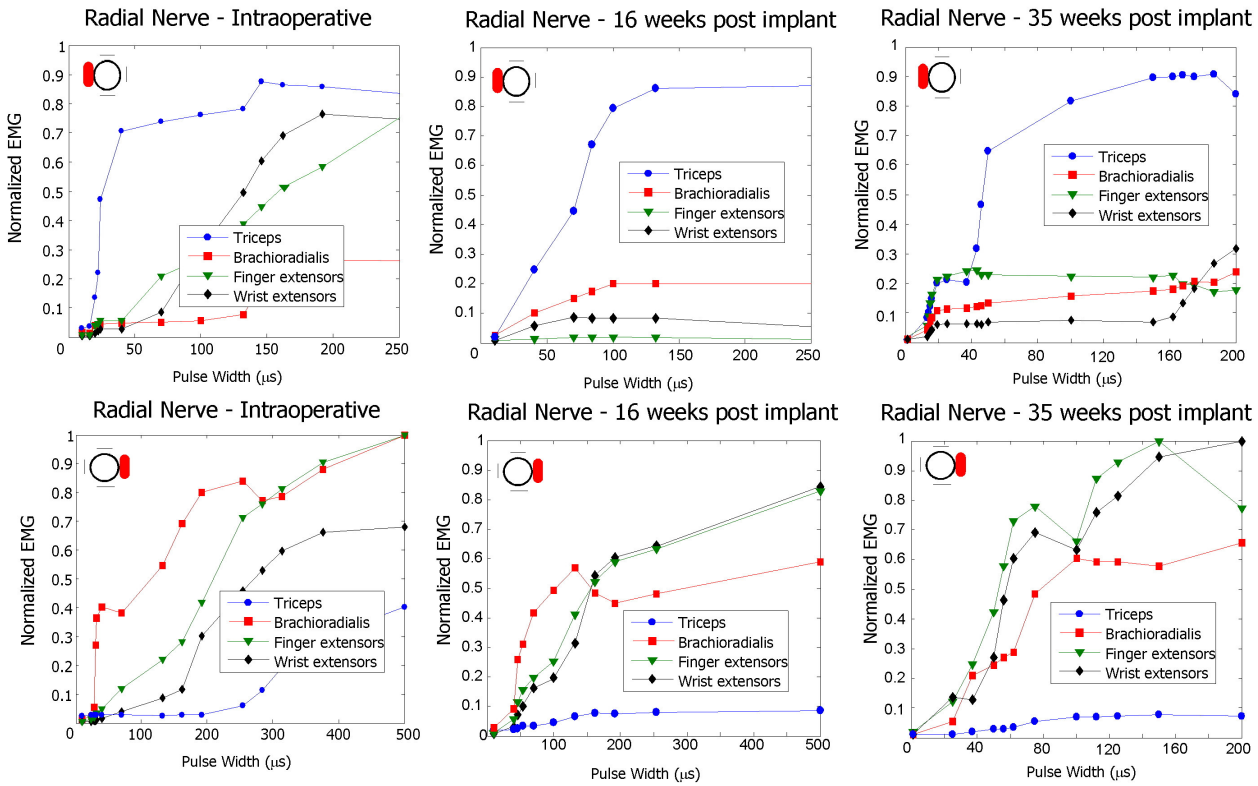

Figure 8. Comparison of radial nerve electrode recruitment from intraoperative testing to 16 and 35 weeks post implant. Each recruitment curve was generated using pulse width modulation with a pulse amplitude of 0.8 mA. The schematic in the upper left hand corner of each plot visually depicts the channel used for simulation. Channel 1 activates triceps first in each case and channel 3 activates triceps last in each case.

Stimulation Thresholds:

The stimulation threshold (10% maximum EMG) was calculated for each EMG recruitment curve (Figure 9). The average threshold at 5 weeks was 35.2 ± 26 nC. At 35 weeks post implant, the thresholds for most channels decreased and the variability between channels decreased. The average threshold at 35 weeks was 11.3 ± 9 nC.

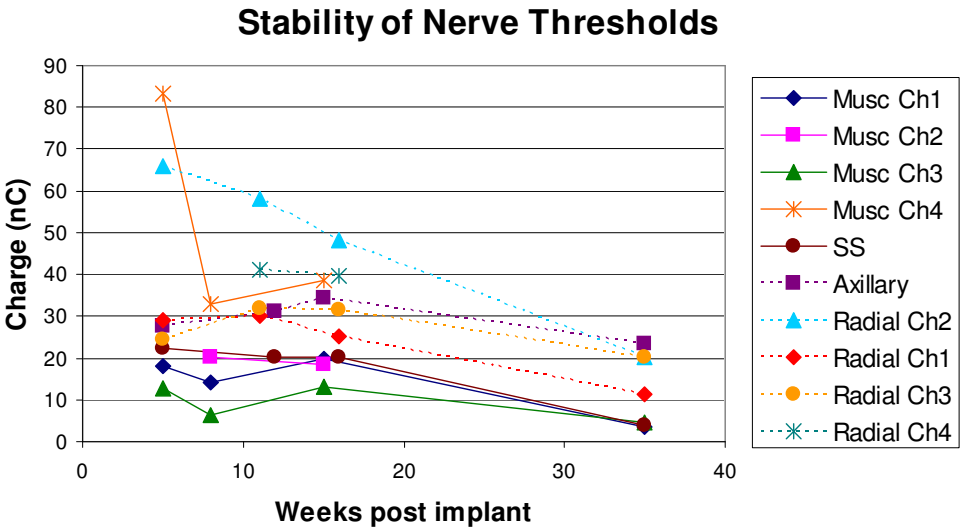

Figure 9. Threshold charge over time from 5 to 35 weeks post implant for each electrode contact. The thresholds for each channel converge after 35 weeks.

The thresholds recorded at the initial session 5 weeks post implant had considerable variation but were still within the range expected based on intraoperative testing of this electrode. Over the course of the trial, the thresholds varied slightly from week to week but at 35 weeks appear to converge. This is not unexpected since tissue encapsulation should stabilize the electrode on the nerve and prevent movement of the electrode relative to the nerve between measurement sessions.

Next Quarter

Percutaneous testing of the nerve cuff electrodes in this subject is complete. Additional moment measurements and surface recruitment curves will be recorded to assess the longer term strength, stability and selectivity of the electrodes.

Laboratory System for FES Controller Development

Contract section: E.1.a.vi.4.3. Implementation of neuroprostheses in high tetraplegia

Abstract

A hardware/software real-time lab testing system has been developed for designing controllers for neuroprostheses. This versatile lab testing system is used to prototype and test different stimulation strategies. It has the ability to record data, process the information and generate the appropriate commands for the stimulator in real time and allow for on-the-fly parameter modification. It is also able to synchronize with other equipment to allow real-time quantitative motion analysis, EMG and force recordings. The system's hardware consists of a single-board computer to control data acquisition. The single board computer controls data acquisition and a Universal External Control Unit (UECU) that commands the implanted neuroprosthesis through a radio frequency link. The system's software operates in a host

computer where the controller application is developed and adjusted using Simulink, Real-Time Workshop and xPC-Target features from MATLAB software.

Methods

Figure 10 shows the lab system used for the development of FES applications. The following is a detailed description of each component:

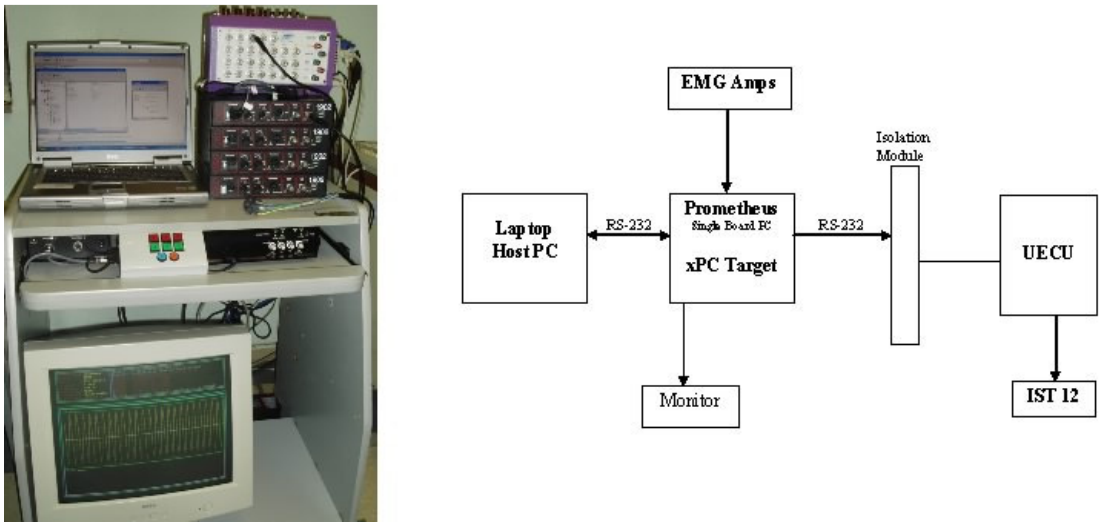

Figure 10. Laboratory System for FES Controller Development.

Hardware

- Host Laptop Computer: Computer hosting Matlab software and communicating with target single board computer through an Ethernet link
- Prometheus Single Board Computer: PC/104 Pentium based 100MHz CPU.
- UECU: Motorola microcontroller based board capable of controlling implantable stimulator through an inductive link.
- Isolation Module: Ensure the patient's safety by providing electrical isolation.
- EMG Amps: Example of acquisition device to integrate to FES system.
- IST-12: Implantable Stimulator Telemeter capable of 12 channels of stimulation and 2 channels of implanted EMG recording.

Software

The host laptop computer runs Matlab software. Several features from Matlab are used to develop FES applications. Real Time Workshop was used for development of a customized toolkit which includes code and Simulink blocks to control the FES implant through the UECU board. The engineer using the system uses Simulink to develop specific subject applications including controller design and data acquisition through the FES implant or any other external device. This is done in a block diagram environment with real-time control and on-the-fly parameter update of the running application.

Results

With this environment we have developed and used several applications for the high level tetraplegia project:

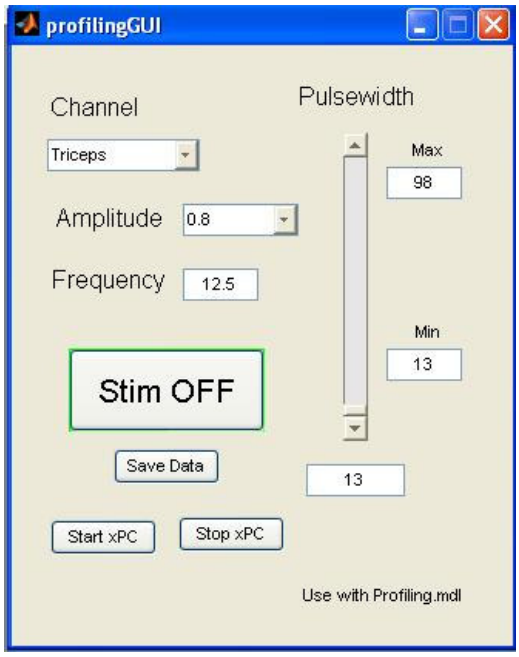

Figure 11. GUI to profile stimulating electrodes.

Figure 11 shows the graphical user interface (GUI) to profile stimulating electrodes. We are able to stimulate any channel in the implant, nerve-cuff or muscle based, with any parameter combination of frequency, current amplitude and pulsewidth.

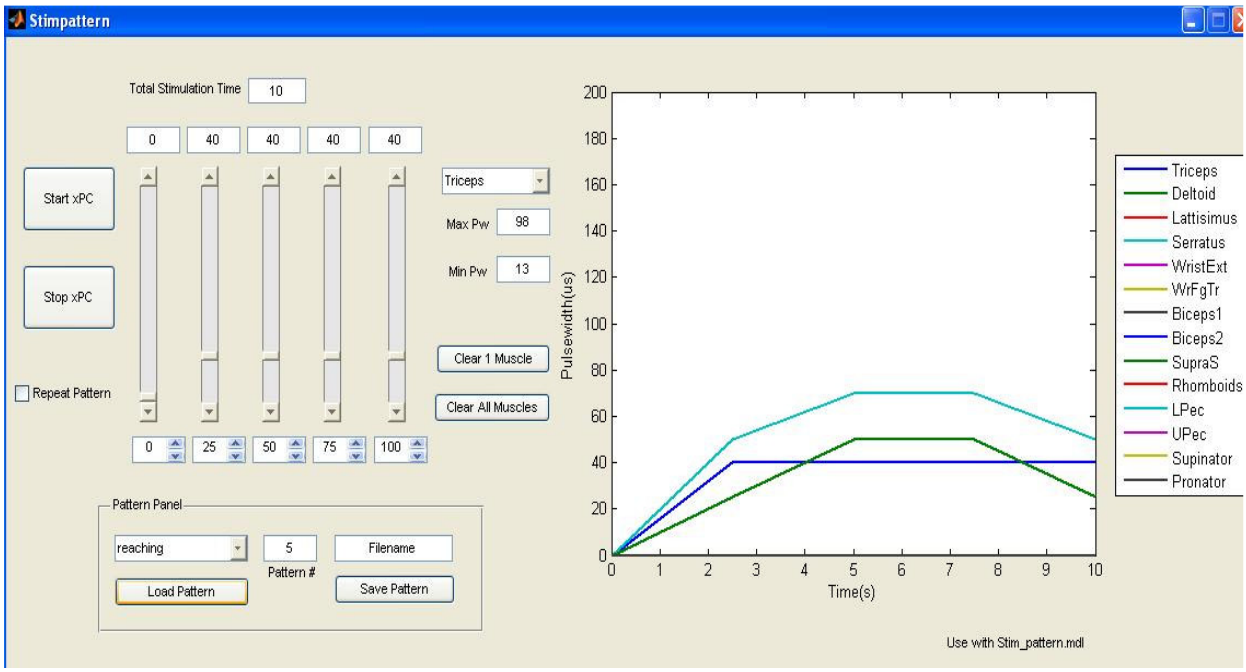

Figure 12. GUI to develop stimulation patterns.

Figure 12 shows the GUI to load, create and save stimulation patterns. It allows for simultaneously stimulating channels with different time profiles. We can use this application to adjust stimulation patterns to achieve functional outcomes.

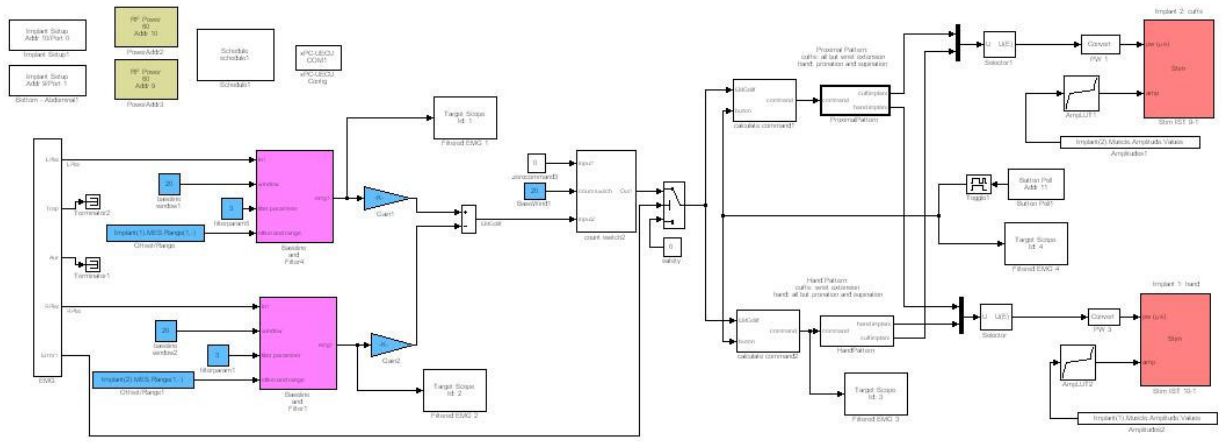

Figure 13. Control Application

Figure 13 shows an example of a control application. In this kind of applications we read the EMG signals from the implant, process them by removing the baseline and using an adaptive filter, and generate a command signal that drives the stimulation in the implant to produce a coordinated response of the muscles, thereby achieving functional outcomes.

Next quarter

We will continue to develop and improve the applications we have created for the development of FES controllers. Specifically we expect to expand the applications to be used by our second subject with two implants including nerve-cuff electrodes with mid-level tetraplegia. Furthermore, we expect to have applications that use our model-based developed controllers based on artificial neural networks and fuzzy logic so that we can try them in real-time with our subjects.

Subject recruitment for neuroprosthesis implementation

Contract section:

E.2.a.ii.4.3 Implementation of advanced upper extremity neuroprosthesis

Summary

In this quarter, the final preparations have been made for the implantation of nerve cuff electrodes in the upper extremity and trunk of a subject with a C5 level spinal cord injury. An individual has been selected to receive the electrodes during the next quarter.

"Improved C5-C6" neuroprosthesis candidate

Individuals with SCI at the C5-C6 level are candidates for the "improved C5-C6" neuroprosthesis. The candidate selected for this study is 43-year-old white male who sustained a

C4/C5 spinal cord injury from a diving accident in 1985. This candidate has C5-level function on both sides (no wrist extension, but can voluntarily activate his brachioradialis). All of the targeted muscles in this study were able to be electrically activated. His right side appears to be slightly stronger and therefore will be the target for the neuroprosthesis.

As with the high tetraplegia subject, the first phase of the neuroprosthesis implantation will involve the implantation of four nerve cuff electrodes, with the leads connected to percutaneous wires for external testing. Since the C5/C6 subject has a lower level injury than the "high tetraplegia" subject, two of the nerves selected for the "high tetraplegia" subject (axillary and musculocutaneous) are under voluntary control and do not need to be stimulated. The four nerves to implement were selected based on previous work in this Contract, including cadaver studies and simulations performed with a model of the shoulder. These four nerves are:

- Radial nerve – four contacts on the cuff could allow selective control of elbow extension, wrist extension, and finger extension.
- Suprascapular nerve – whole nerve stimulation for stabilizing the rotator cuff capsule and humeral rotation (supraspinatus, infraspinatus).
- Thoracodorsal nerve – whole nerve stimulation for shoulder adduction and extension (latissimus dorsi).
- Long thoracic nerve – whole nerve stimulation for scapular abduction (serratus anterior).

Surgical preparation

Nerve cuff electrodes have been fabricated with cuff diameters that are appropriate for the above nerves based on earlier cadaver work. Electrode lead lengths were determined from measurements on each subject of the predicted lead routes. The nerve cuff electrode implantation technique will be the same as that used in the intraoperative nerve testing studies and in the high tetraplegia candidate, both discussed in previous progress reports. All necessary regulatory approvals have been obtained. The candidate is scheduled to have surgical implantation of nerve cuff electrodes in the next quarter.